| REPORT DOCUMENTATION PAGE | *Form Approved* *OMB No. 0704-0188* |
|---|---|



| 1. REPORT DATE *(DD-MM-YYYY)* | 2. REPORT TYPE | 3. DATES COVERED *(From - To)* |
|---|---|---|
| 26-07-2006 | Final report | 01-10-2004 - 03-29-2006 |

**4. TITLE AND SUBTITLE**

Final report: High bandwidth atomic detection at the single-atom level and cavity quantum electrodynamics on an atom chip

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**

FA9550-04-1-[redacted] 0461

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**

Dan Stamper-Kurn

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

University of California, Berkeley, CA 94720

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

Air Force Office of Scientific Research
Physics and Electronics Division
875 Randolph Street, Suite 324
Arlington, VA 22203-1768

**10. SPONSOR/MONITOR'S ACRONYM(S)**

AFOSR

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

**12. DISTRIBUTION/AVAILABILITY STATEMENT**

Distribution A: Approved for Public Release

AFRL-SR-AR-TR-07-0028

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

The overall objective of this seedling grant was integrate high-finesse optical cavities onto atom chips so as to advance the application of cavity quantum electrodynamics (CQED) to ultracold atoms for applications in sensing, quantum information, technology exploration and basic science. We have accomplished all of the experimental objectives for this project. Extensive research and testing of various microfabrication methods yielded a robust recipe for integrating small-scale high-finesse mirrors onto sapphire and glass substrates. The challenges of temperature variations on and vibrational coupling to the chip were addressed effectively. We fabricated a sapphire-substrate atom chip with integrated Fabry-Perot cavity and a temperature stabilization system. The high-finesse cavity achieving the single-atom strong-coupling regime for rubidium atoms, and was kept locked during a simulated operation of the atom chip.

**15. SUBJECT TERMS**

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | 19b. TELEPHONE NUMBER *(Include area code)* |

# Final report: high bandwidth atomic detection at the single-atom level and cavity quantum electrodynamics on an atom chip

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## 1 Objectives

The overall objective of this seedling grant was integrate high-finesse optical cavities onto atom chips so as to advance the application of cavity quantum electrodynamics (CQED) to ultracold atoms for applications in sensing, quantum information, technology exploration and basic science. As stated in our proposal at the start of this effort, our objectives were fourfold:

1. assessment of designs and fabrication methods,
2. materials development wherein fabrication methods are implemented,
3. development of the infrastructure to test the CQED/atom chip hybrid systems, and
4. theoretical work to inform the later operation of on-chip CQED devices.

A major change from these originally stated goals was the expansion of our experimental effort to address challenges which we uncovered during our work. These additions include the following:

5. assembly and testing of vibration isolated and temperature controlled heat sinks suitable for mounting CQED/atom chip devices so that high-finesse cavities can be frequency locked which simultaneously supplying high currents to and generating electrical heat on the atom chips
6. development of a microfabricated temperature measurement and stabilization system which is integrated into an atom chip
7. design and implementation of an alterative approach to CQED/atom chip integration based on silicon-substrate chips (see below)

## 2 Status of effort

We have accomplished all of the experimental objectives for this project. Extensive research and testing of various microfabrication methods yielded a robust recipe for integrating small-scale high-finesse mirrors onto sapphire and glass substrates. The quality of these mirrors, with dimensions ranging from $\sim 50 - 200$ $\mu$m, were tested by cavity ring-down methods. These tests revealed no degradation of mirror reflectivities, even for mirrors with total losses of only 15 ppm. Fabry-Perot cavities formed using these mirror pads achieved conditions well in the strong-coupling regime of cavity QED with rubidium atoms, e.g. a critical atom number of $1 \times 10^{-2} \ll 1$ and critical photon number of $6 \times 10^{-4} \ll 1$.

Temperature variations on and vibrational coupling to the chip were identified as major challenges to integrating mirrors onto an atom chip. To address these, two successful strategies were implemented for extracting heat from the atom chip while maintaining sufficient vibrational isolation and maintaining UHV conditions. Further, we developed a microfabricated temperature sensor and stabilization system which operates successfully at high bandwidth (> 1 kHz), and which is of general use for atom chips and their future application.

Combining these developments, we fabricated a sapphire-substrate atom chip with integrated Fabry-Perot cavity and temperature stabilization system. The high-finesse cavity attained parameters achieving the single-atom strong-coupling regime for rubidium atoms, and was kept locked during a simulated operation of the atom chip. A paper describing this experimental success, which culminates our seedling effort, is in preparation.

We additionally explored an alternative strategy to incorporating cavity QED onto atom chips, one which permits only longer (spectally narrower) cavities than is possible with the sapphire design, but which mitigates many of the concerns about vibration and thermal coupling between the atom chip and the cavities. We successfully carried out all essential steps with this silicon-based design, and have begun constructing an apparatus which will use a silicon-based CQED/atom chip for experiments in atom optics, quantum measurement and control.

## 3 Accomplishments and new findings

The goal of our atom-chip work has been to effectively integrate atom chip and cavity QED technologies so that complex ultracold atom experiments could be carried out using strong-coupling cavities for single and multiple atom detection, for coherent atom manipulation, and for atom-atom or atom-photon entanglement. The challenge to achieving this goal is creating high-finesse optical cavities which maintain their finesse even given the requirements for the atom chip of having optically opaque, heat-sourcing electromagnets physically close to the atoms. We have taken on that challenge by advancing two designs, one in which half of the (Fabry-Perot) cavity is integrated physically onto a sapphire substrate atom chip, and a second in which both cavity mirrors are separate from a silicon based atom chip. Both designs have been successfully implemented and tested. We have therefore begun constructing an experiment in quantum atom optics which utilizes such a device.

### 3.1 Sapphire-based chips

One design for the CQED/atom chip integration involves placing planar high-reflectivity mirrors on the same surface that supports the atom-chip electronics (Fig. 1). Given that high-reflectivity dielectric mirrors require that the dielectrics be uniformly deposited directly onto a superpolished substrate, our design starts with a large diameter dielectric mirror from which, by microfabrication techniques, the dielectric coatings are etched away selectively from locations at which the atom-chip electromagnets are then placed. The cavity is completed by a second, curved mirror mounted above the planar surface. Compared with the silicon-based design discussed below, this approach allows for much shorter optical cavities that have broader resonance widths and also, due to their smaller mode volume, strong light-atom interaction strengths. This makes such cavities easier to stabilize and probe and permits higher bandwidth atomic detection and manipulation. Further, the sapphire-based design represents a more ambitious integration of optical systems directly onto atom chips. Ultimately, such integration ("optoatomtronics") could add valuable capabilities to atom chips, e.g. optical waveguides, beam splitters, Bragg gratings and other microstructured potentials [1, 2], and may also permit much higher densities of CQED devices on chip.

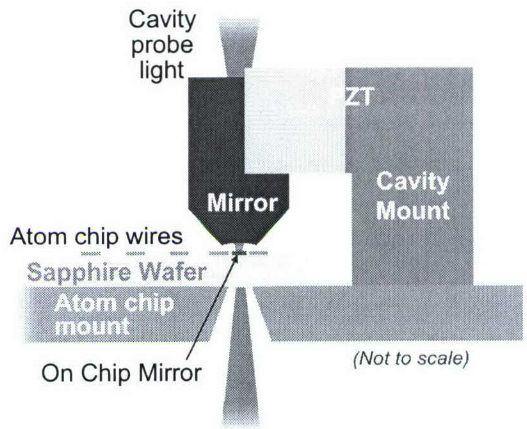


Figure 1: Scheme for integrating cavity QED onto atom chips on a sapphire substrate. Microfabricated atom chip elements and mirror pads are formed atop the sapphire substrate. A separate, curved mirror is held above the chip and actuated using a piezoelectric transducer (PZT) to maintain a fixed cavity resonance. The clear sapphire substrate allows for interrogation of the cavity by sending light through a clear opening in the atom chip heatsink.

Implementing this scheme requires overcoming challenges both during fabrication and also during operation of the hybrid atom chip. At the start of our effort, it remained an open question whether the many steps in fabricating atom chips would necessarily degrade the quality of state-of-the-art mirrors on the chip surface such as are necessary to access cavity QED in the strong-coupling regime. We proceeded to address this question first by determining suitable methods for producing the dielectric mirror pads. A variety of fabrication techniques were explored using readily-available high reflectivity mirrors on glass substrates (Newport Corp.), on uncoated sapphire flats, and then finally on ultrahigh-reflectivity sapphire-substrate mirrors (REO, Boulder). To create the mirror pads, an evaporated aluminum mask was applied to to protect portions of the mirror during plasma etching of the dielectric coatings from the remaining area. Plasma etching was chosen because it effectively removes the dielectric mirror coatings while attacking sapphire at a much slower rate, thus allowing the etching to self-terminate once the substrate is exposed. Fig. 2 shows an image taken of one such micropatterned mirror, showing circular and rectangular "mirror pads" which remain while the dielectric coatings elsewhere are etched away completely.

Mirror qualities were tested by assembling half-planar Fabry-Perot cavities using the mirror pad and a separate, curved, highly-reflective and well-characterized mirror. Three sapphire-substrate mirrors were used for these tests:

- **REO 2-5:** This mirror was tested before any microfabrication was carried out. The mirror quality varied as cavities were formed on different small spots off the 2" diameter surface. The highest measured finesse was $\mathcal{F} = 4.5 \times 10^5$, implying losses as low as $< 4$ ppm for this sapphire mirror.

- **REO 2-2:** Test arrays of mirrors and atom-chip wires were fabricated on this chip. Cavities with finesses of $\mathcal{F} = 2.4 \times 10^5$ were observed on mirrors with no visible blemishes, both on the patterened and unpatterned regions, implying $\sim 15$ ppm losses for this mirror. For example, a nominally 100 $\mu$m diameter mirror pad (minus about 12 $\mu$m due to etching of the mirror edges) was used to form a 25 $\mu$m long Fabry-Perot cavity with a FWHM linewidth of 26 MHz. Such a cavity is well in the strong-coupling regime of cavity QED: the vacuum Rabi splitting of $g = 2\pi(88 \times 10^6)\,\mathrm{s}^{-1}$, cavity half-linewidth of $\kappa = 2\pi(13 \times 10^6)\,\mathrm{s}^{-1}$, and atomic half-linewidth of $\gamma = 2\pi(3 \times 10^6)\,\mathrm{s}^{-1}$ give a critical atom number of $2\kappa\gamma/g^2 = 1 \times 10^{-2} \ll 1$ and critical photon number of $\gamma^2/2g^2 = 6 \times 10^{-4} \ll 1$.

  These tests indicate that no significant damage was caused to the mirror pads during the entire microfabrication process. Using the micropatterned mirrors, the cavity finesse was found to degrade for sufficiently long cavity spacings, plausibly due to diffractive losses on the micropatterned mirror edge which worsen as the cavity mode width grows with increased spacing.

- **REO 2-4:** Complete assemblies of atom-chip elements and mirror pads were fabricated on this mirror, such as that shown in Fig. 3. Mirror pads on this substrate showed slight blemishes under a microscope, and gave lower cavity finesses $\mathcal{F} = (6 - 9) \times 10^4$, although these blemishes were absent in later microfabrication attempts. These assemblies were used to demonstrate the ability to maintain the cavity resonance fixed during simulated operation of an atom chip.

Summarizing these tests, micropatterned mirrors were found to have reflectivities matching those of the original unprocessed mirrors, that is, that no damage was caused to the mirror pads during the entire microfabrication process. The yield of such mirror pads was not 100%, as, on occasion, visible blemishes were produced during microfabrication or in later handling of the mirrors. The cavities integrated into atom-chip structures achieved the single-atom strong-coupling regime. Cavity finesses were diminished by predictable diffraction losses when the cavities were excessively long, so that the mode size at the small mirror pad became larger. Significant birefringence effects (separations by several linewidths) were apparent for non-circular mirror pads, presumably resulting from asymmetric stresses on the asymmetrically-shaped dielectric coatings forming the mirror.

Our group developed expertise in fabricating atom chips following a visit to the Prentiss group at Harvard University. Adapting these techniques to substrates containing mirror pads was straightforward. While the mirror pads acted as barriers to the smooth flow of spun-on photoresist solutions during fabrication, we found that applying a sufficiently thick layer of photoresist overcame this problem and allowed for atom chip elements to be fabricated within several microns of the edge of the mirror pads. We also found that leaving the evaporated aluminum mask atop the mirror surface throughout the atom-chip fabrication process provided effective protection of the mirror.

The resulting atom chip and high-reflector assembly is shown in Fig. 3. Rectangular and circular mirror pads are flanked by current-carrying copper wires which produce a tight waveguide for ultracold atoms above the mirror surface. These wires are closely spaced (200 $\mu$m) so that, at reasonable (few ampere) currents and bias fields, the waveguide attains the Lamb-Dicke regime wherein the rms spatial width of a guided atomic beam can be less than an optical wavelength.

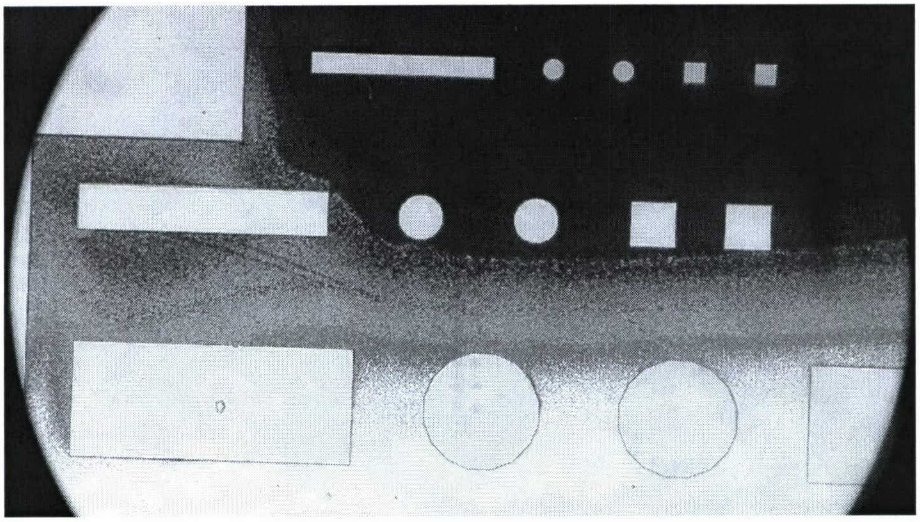

Figure 2: A magnified image showing microfabricated mirrors formed from a BK7 substrate supermirror from Newport Corp. Objects in the top row have a 100 micron minimum feature size, those in the center a 200 micron size, and those in the bottom row a 500 micron size. The bright features show the dielectric mirror coating while the darker background reveals the regions completely etched away, down to the substrate. Note that on a BK7 substrate, the etching does not terminate at the substrate, unlike with sapphire.

Attaining this criterion is important since the optical modes in a Fabry-Perot cavity are standing waves in which the electric field strength varies sinusoidally with a period of half an optical wavelength. Confinement at the Lamb-Dicke regime thus allows guided atoms to be probed at well-defined atom-light interaction strengths, simplifying the operation of CQED devices.

From the outset of our work, it became apparent that an atom chip is a challenging platform on which to house a high-finesse optical cavity. That is, stabilizing the resonance frequency of a cavity with finesse $\mathcal{F}$ to better than the cavity linewidth requires that the effective mirror spacing (including possible phase-shifts at the mirror surfaces) be held fixed to within $\delta x \ll \lambda/\mathcal{F}$, where $\lambda$ is the resonant optical wavelength. For the values $\mathcal{F} \sim 10^5$ attained in Fabry-Perot cavities suitable to CQED, the mirror spacing must be held constant within less than a picometer. Such stability is typically achieved experimentally by aggressively isolating the cavity from high-frequency vibrations, and then using feedback (limited to $\lesssim 10$ kHz due to mechanical resonances) at lower frequencies. The need to operate an atom chip in contact with the Fabry-Perot cavity mirror adds challenges to such a strategy. An electromagnet-based atom chip requires several-ampere electrical currents and also sufficient thermal conduction to a heat sink to dissipate the resistive heat load. Stiff electrical and thermal conductors would act to defeat the vibration isolation required to stabilize the high-finesse optical cavity. Further, as electromagnets are powered on and off during an experimental cycle, the sapphire substrate below one of the cavity mirrors will vary in temperature. The resulting thermal expansion and contraction of the substrate varies the mirror spacing by nanometer-scale distances (far larger than the $\delta x$ tolerance discussed above) at rapid

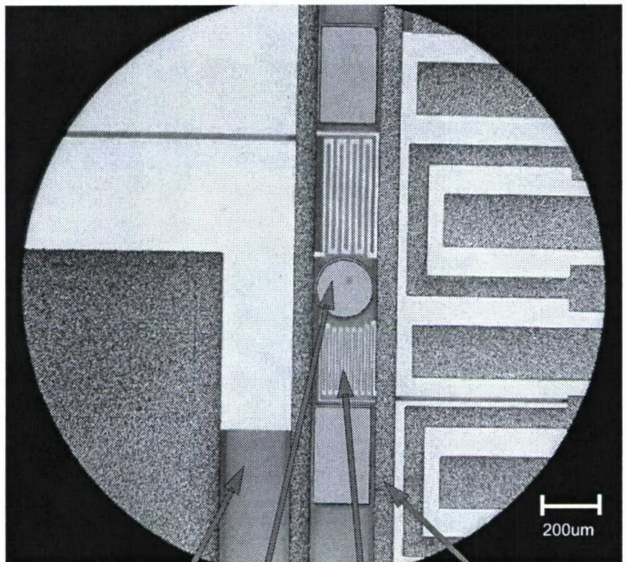


Figure 3: Portion of sapphire-based CQED/atom chip. The central vertical column in the image shows two rectangular (top and bottom) and one circular mirror pad which were formed by microfabrication from a highly reflective dielectric mirror on a sapphire substrate. On-chip platinum RTD and resistive heater are shown above and below the circular mirror, respectively. Electroplated copper wires appear as mottled surfaces, and include a two-wire waveguide (flanking the mirrors), and portions of a magnetic conveyor system. The remaining features (smooth appearance) are the sapphire substrate which is either uncoated or coated with a thin $SiO_2$ layer. A chip assembly similar to the one pictured was operated successfully in a simulation of actual use with ultracold atoms.

($\sim$ ms) timescales, making it difficult to maintain a precise cavity mirror spacing by feedback or feed-forward.

To address the issue of vibration isolation, we assembled a multi-stage vacuum-compatible vibration-isolated atom chip mount comprised of heavy copper plates separated by compressed viton springs (Fig. 4). Electrical and thermal conduction between these plates was provided by many parallel thin copper ribbons which are strain-relieved at each of the copper plates. Thin polyimide films provide electrical isolation. Isolation of better than 30 dB at frequencies above 200 Hz was achieved. An alternate approach that uses thermal radiation to conduct heat to a cryogenically-cooled heat sink was also successfully assembled. While this approach provides greater vibration isolation by eliminating material thermal conductors, it was deemed unnecessarily cumbersome for the present application.

To address the difficult problem of temperature variations of the on-chip mirror due to a varying electrical heat load, we developed the means to actively stabilize the temperature of the cavity

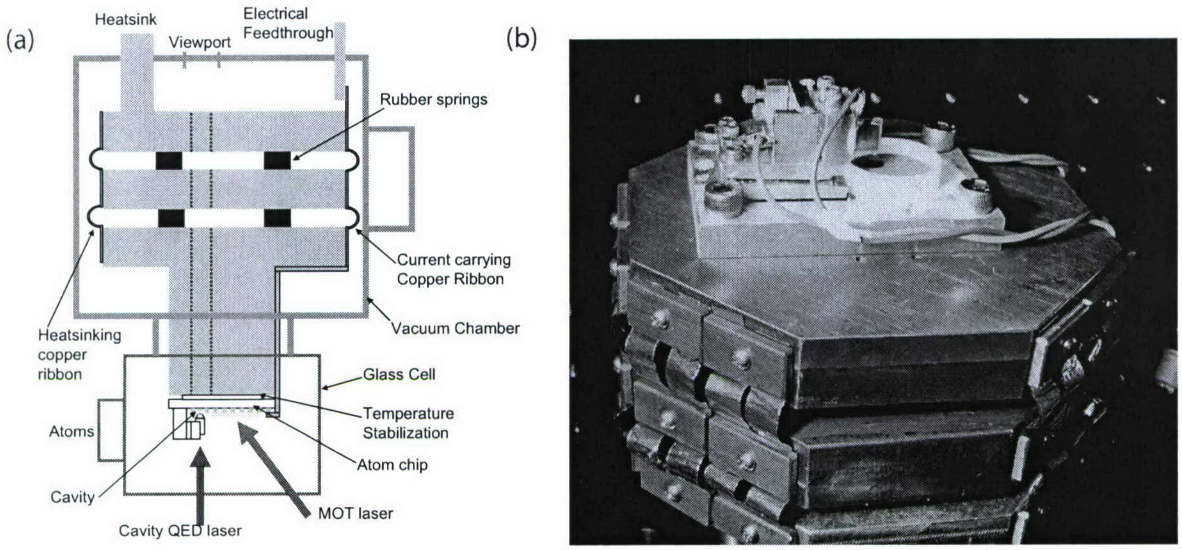


Figure 4: Vibration isolation stack for CQED/atom chip. (a) Schematic drawing shows a two-stage vibration isolation stack comprised of copper masses separated by compressed viton springs. In this geometry, the top mass is connected rigidly to the vacuum chamber while the vibration isolated atom chip is attached to the bottom mass. Thermal and electrical conduction is provided through flexible copper ribbons. This design was tested to provide sufficient vibration isolation and UHV compatible. (b) A photograph of such an isolation stack, mounted with the atom chip on top, is shown. A small high-finesse mirror (coated surface on the bottom) is held above a 1 inch diameter glass-substrate mirror on which micropatterned mirror pads were formed. Electrical leads control a piezoelectric transducer used to tune and stabilize the cavity resonance.

mirror. This is accomplished by making local on-chip temperature measurements using a microfabricated RTD, and feeding back to the current driven through a nearby resistive heater. These two on-chip platinum structures are shown in Fig. 3. An AC bridge circuit and lock-in detection allowed for low-noise temperature measurements limited only by thermal Johnson noise of the RTD. AC operation of the RTD would also prevent disturbances to magnetically-trapped atoms near the thermometer. The temperature stabilization afforded by this system was remarkably powerful, operating at bandwidths in excess of 1 kHz.

The final objective of our seedling effort was to test the CQED/atom chip under conditions simulating the operation of the chip in an ultracold-atom experiment. To wit, our goal was to stabilize an on-chip cavity with finesse of $\mathcal{F} \sim 3 \times 10^4$ — a typical value for the off-atomic-resonance light use to stabilize the cavity during experiments — while powering on and off the co-located waveguide with currents of several amperes. This goal was achieved. The temperature stabilization circuit provided sufficient damping of the thermal disturbances to the mirror so that the cavity resonance lock was reacquired at each on-off cycle of the waveguide.

### 3.2 Silicon-based design

We also followed an alternate approach to integrating high finesse cavities with atom chips. Here the idea is to avoid the issues involved with heating (and vibrations) on the atom chip entirely by having the cavity mounted separately from the atom chip. Keeping with a vertical orientation of the Fabry-Perot cavity (relative to a horizontal atom chip), we are pursuing a system in which the atom chip passes between the two mirrors forming the cavity (Fig. 5). The atom chip is made as thin as possible so that the spacing between the mirrors can be kept low, while the optical mode passes through a micromachined hole in the atom chip. The advantage of this scheme is that heating on the atom chip no longer affects the optical cavity, that all high reflectivity cavity mirrors can be reused even as the atom chip is redesigned, and that the atom chip is now much easier and cheaper to fabricate.

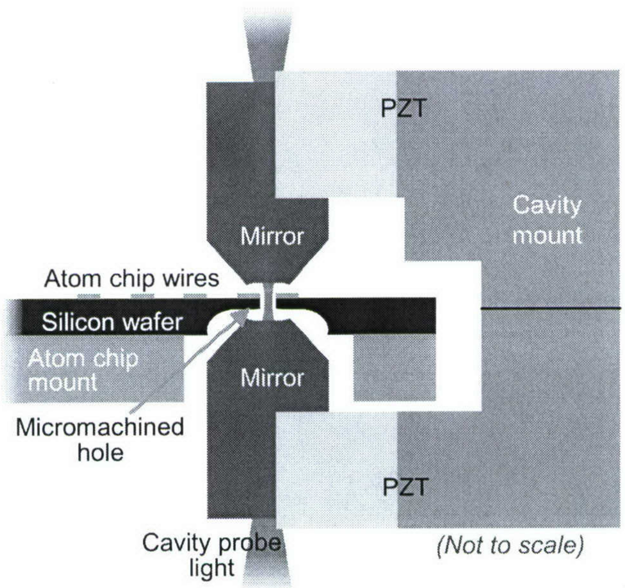


Figure 5: Design scheme for a silicon-based atom chip integrated with high-finesse optical cavities. Here, the optical cavity is formed from two highly reflective mirrors separate from the chip. This decouples heating and vibration on chip from the optical cavity, promising a more stable setup. The cavity mode pierces the silicon chip through micromachined holes. These 100 $\mu$m holes are small enough to allow surrounding electromagnets to tightly confine atoms and guide them through the cavity.

We tested the limits of how thin the atom chip can be made while still providing sufficient thermal conduction to accommodate the heat produced locally by electromagnet wires. For this, we took 500 $\mu$m thick standard silicon wafers and then etched a 2 mm diameter "crater" of variable depth on one face of the wafer. A thin wire was then formed on the other face of the wafer, and then the wire-breaking current was determined for different depths of the crater, corresponding to different total widths of the silicon chip. We found that silicon wafers thinned down to as little as 100 $\mu$m showed no significant deterioration in performance. Thinner wafers have not yet been tested. We expect that the atom chip material between the two cavity mirrors can have a total thickness, including the electroplated wires, of 80 $\mu$m or less, while strong coupling cavities with mirror spacings of 200 $\mu$m would already by suitable for our work. We have also now debugged the process for etching the hole through which the cavity-mode light will pass. We find deep reactive ion etching (DRIE) to work well for this purpose.

# 4 Personnel supported

1. Shin Inouye, postdoc, Jan. 2005 – Apr. 2005.
2. Thomas Purdy, graduate student, Jan. 2005 – Jan. 2006.

# 5 Publications

1. T. Purdy and D.M. Stamper-Kurn, "Integrating cavity quantum electrodynamics and ultracold-atom chips with on-chip dielectric mirrors and temperature stabilization," in preparation (2006).

# 6 Interactions/Transitions

## 6.1 Meetings, conferences, seminars

1. D.M. Stamper-Kurn, Atomtronics Kickoff Meeting, Boulder CO. Invited talk entitled "Cavity quantum electrodynamics on an atom chip," September 2004.
2. D.M. Stamper-Kurn, David and Lucile Packard Fellows Annual Meeting, Monterey, CA. Poster entitled "Non-linear optics and magnetism in a Bose-Einstein condensate" October 2004.
3. D.M. Stamper-Kurn, Brigham Young University, Provo, UT. Colloquium entitled "New approaches to imaging Bose-Einstein condensates" February 2005.
4. D.M. Stamper-Kurn, Banff Cold Atoms Meeting, Banff, Alberta, Canada. Poster entitled "Seeing spinor Bose-Einstein condensates," February 2005.
5. Chaired session on "BEC and trapped Bose gases" at APS March Meeting 2005, Los Angeles, CA. May 2004.
6. D.M. Stamper-Kurn, MIT/Harvard Center for Ultracold Atoms, Harvard University, Cambridge, MA. Invited talk entitled "New approaches to imaging Bose-Einstein condensates," May 2005.
7. T. Purdy, S. Gupta, K. Moore, K. Murch, D.M. Stamper-Kurn, DAMOP 2005, Lincoln, NE. Poster entitled "Cavity QED and atom chips," May 2005.

8. D.M. Stamper-Kurn, "Seeing spinning condensates." University of Milan, Milan, Italy, July 2005.
9. D.M. Stamper-Kurn, "Seeing spinning condensates." Manipulating Quantum Systems, Monte Verita, Ascona, Switzerland, July 2005.
10. D.M. Stamper-Kurn "Seeing spinning condensates." Center for Advanced Studies Thursday Seminar Series, University of New Mexico, Albuquerque, New Mexico, August 2005.
11. D.M. Stamper-Kurn, "Seeing spinning condensates." Quantum Lunch, Los Alamos National Laboratory, Los Alamos, New Mexico, August 2005.
12. Chaired session on "Coherent atoms and matter waves I" at CLEO/QELS Meeting 2006, Long Beach, CA. May 2006.
13. Thomas Purdy, Dan Stamper-Kurn, "Toward cavity QED on an atom chip," DAMOP, Knoxville, TN. May 2006.

### 6.2 Consultative activities

1. Participated in advisory meeting (Sept. 2005, Boulder, CO) to DoD agencies on future of atomtronics and prospects for new funding program.
2. Participated in "Workshop on Quantum analog simulations of quantum condensed-matter models," held in Washington, D.C. in April 2005, advising DoD agencies on applications of lattice-trapped neutral-atom systems to open problems in many-body and computational physics.

### 6.3 Technology transitions

None

## 7 New discoveries

None.

## 8 Honors and awards received during granting period

None.

## References

[1] Ying-Ju Wang et al. An atom michelson interferometer on a chip using a bose-einstein condensate. *Physical Review Letters*, 94:090405, 2005.

[2] Katharina Christandl et al. One- and two-dimensional optical lattices on a chip for quantum computing. *Physical Review A*, 70(3):032302–4, 2004.